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Battlefield Applications for the Polatomic 2000 Magnetometer/Gradiometer

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ABSTRACT

This paper describes proposed battlefield applications for the POLATOMIC 2000 (P-2000), an optically pumped He^4 scalar magnetometer/gradiometer. A major innovation in the P-2000 helium magnetometer is the introduction of a laser pump source to replace the conventional RF discharge helium lamp used in the Navy AN/ASQ-81/208 MAD Set for airborne submarine detection. The P-2000 scalar magnetometer developed at Polatomic under sponsorship from ONR/NAVAIR achieves a sensitivity improvement of a factor of 25 to 30 over the AN/ASQ-81/208. Results are discussed for Polatomic 2000 magnetometers operated on the Earth's surface as short baseline gradiometers demonstrating a magnetometer sensitivity approaching 0.1 pTrms/√Hz for detecting small signals in the frequency band from 0.01 Hz to 120 Hz. Performance of the P-2000 internal gradiometer, utilizing two helium cells on 31 centimeter spacing to achieve sensitivity approaching 0.1 pTrms/√Hz per ft, is also discussed. Performance results for the POLATOMIC 2000 in airborne applications are presented, and adaptation of this system to a UAV platform for battlefield surveillance is also described.

1. INTRODUCTION

The Polatomic 2000 magnetometer is a scalar He^4 instrument used to monitor the total magnitude of Earth's magnetic field. The feature that places this instrument in a new class is the very low level of instrument contributed noise in the overall field measurement. This new class of sensitivity is made possible due to a combination of advancements in optical pumped magnetometers achieved under ONR/NAVAIR/DARPA funded research and development programs. The series of programs leading to the Polatomic 2000 design developed a new light source for the optical pumping technology. The new source is a laser diode. When the conventional lamp pump source is replaced with a laser source the optical pumping efficiency shows dramatic improvement. Precision wavelength tuning and noise reduction techniques in the laser diode control electronics are required to realize the improvement. Once the laser tuning has been accomplished, the required wavelength must be maintained over long periods without drift. Wavelength drift translates into noise and loss of sensitivity. When the laser is precisely tuned to the resonance line at 1083nm, signal to noise is much greater than that obtained using a lamp pump source. Measurements made with the Polatomic 2000 magnetometer have demonstrated this sensitivity improvement. Figure 1 shows a typical example of the sensor output when digital processing has been applied. This spectral density plot was made using the data from two channels of a single Polatomic 2000 sensor. The data were digitally captured during testing by Polatomic at our magnetic test site located on the campus of the University of Texas at Dallas. Note the high level of coherence between the two sensors. It is hard to find an area that the two plots are not identical. The third trace in Figure 1 is the noise subtraction of the output from each sensor. This differenced output of the two magnetometer channels yields a gradiometer output containing the combination of sensor noise from each Polatomic 2000 channel and any uncorrelated environmental noise sources such as

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the 60 Hz magnetic fields induced by power lines. Note the excellent coherence of these noises yielding a sensor noise figure of 0.3pTrms/√Hz.

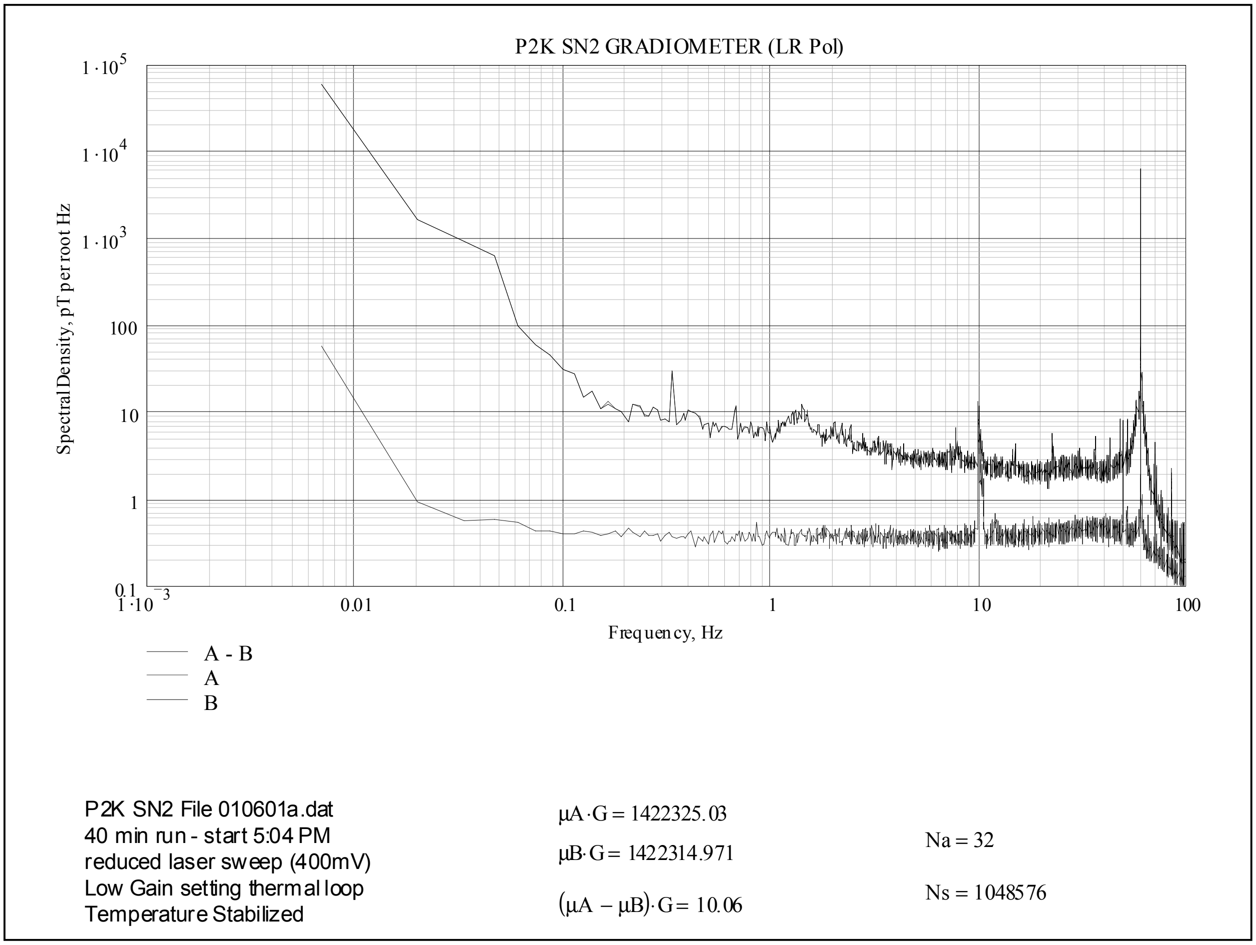

Figure 1. Noise spectral density plot of Channels A and B (two channels in overlapping upper traces) and 31cm gradiometer (lower trace).

2. DESCRIPTION OF THE POLATOMIC 2000 MAGNETOMETER

Operation of the basic sensing element depends on the light-absorption properties of metastable helium atoms simultaneously subjected to optical pumping radiation and resonant radio frequency (H_1) radiation. The basic sensing elements are shown in Figure 2. The optical pumping source in the laser magnetometer is a distributed Bragg reflecting (DBR) diode laser (DL). The diode is electronically controlled and emits light at the wavelength required to optically pump the helium atoms inside the glass helium cell. Before the light enters the cell it is circularly polarized. The light travels through the helium cell to the infrared (IR) detector. A portion of the light is absorbed in the helium cell. The IR detector converts the light energy to an electronic signal and phase information contained in the signal is detected and sent to the digital oscillator that tracks the Larmor frequency f_0. The RF output from the oscillator is used to drive a coil at 90 degrees to the light path and located near the helium cell. A low-frequency modulation

of the RF produces a signal at the modulation frequency, which is used to lock the resonance control loop. Resonance is obtained when maximum light is absorbed in the cell.

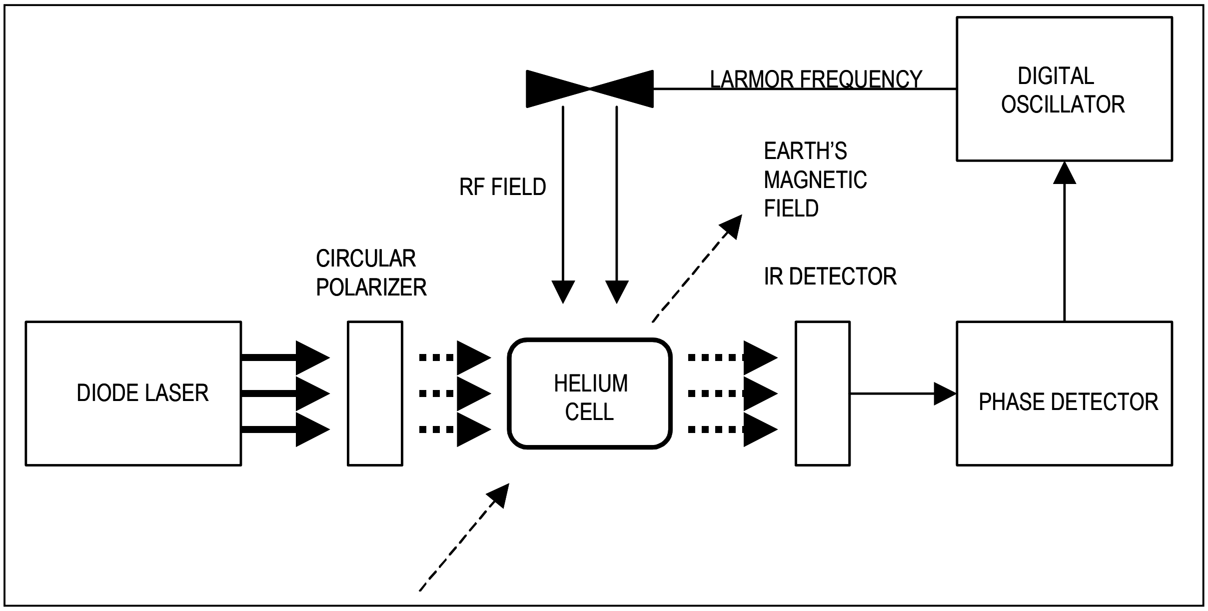

Figure 2. Basic sensing elements of the laser-pumped magnetometer loop are shown.

The Larmor frequency f_0 is directly proportional to the applied magnetic field and is given by:

$$f_0 = g\, H_{0,}$$

where

H_0 = magnetic field in nanoTesla
g = gyromagnetic ratio of helium atom
= 28.0235 Hz/nT

The P-2000 has the following performance characteristics:

Range	22,302 to 78,058 nanoTesla (nT)
Resolution	83.1 x 10^{-6} nT
Noise Level	0.3 picoTesla (pT)/√Hz (0.5 to 50 Hz)

The P-2000 sensor contains two helium cells pumped from a common laser. In a normal operating mode the two cells are used to reduce the common mode noise from the pump source. This mode is referred to as the Dual Cell operating mode. Dual Cell mode operation results in one total field scalar output from the magnetometer. The system output is a 32 bit digital word representing the total field intensity at a point midway between the A and the B helium cells. The cells are positioned along the vertical axis with respect to the ground when the sensor is installed in the tail boom of a P-3 aircraft. Resonance loop lock will be maintained as long as the vertical axis of the sensor is within 60 degrees of the magnetic dip at the measurement location. ONR is currently sponsoring development of an omni directional laser pumped sensor design having the same sensitivity on all headings. An omni directional sensor configuration is desired for worldwide operation on moving platforms. Stationary sensor ground

testing does not require an omni sensor as long as the alignment is maintained to within 60 degrees of the field direction. The P-2000 is therefore ideally suited for battlefield sensing applications.

A second P-2000 operating mode is also available. This mode is called the Gradiometer operating mode. Two independent total field measurements are made when this mode is active. The A cell and the associated coils and drive electronics form one magnetometer and the B cell and the associated drive electronics form another magnetometer. The distance between the two cells is 31 centimeters. The laser and associated drive electronics are common to each channel. Each magnetometer maintains the same measurement resolution in the gradiometer mode. A Gradiometer mode block diagram is shown in Figure 3.

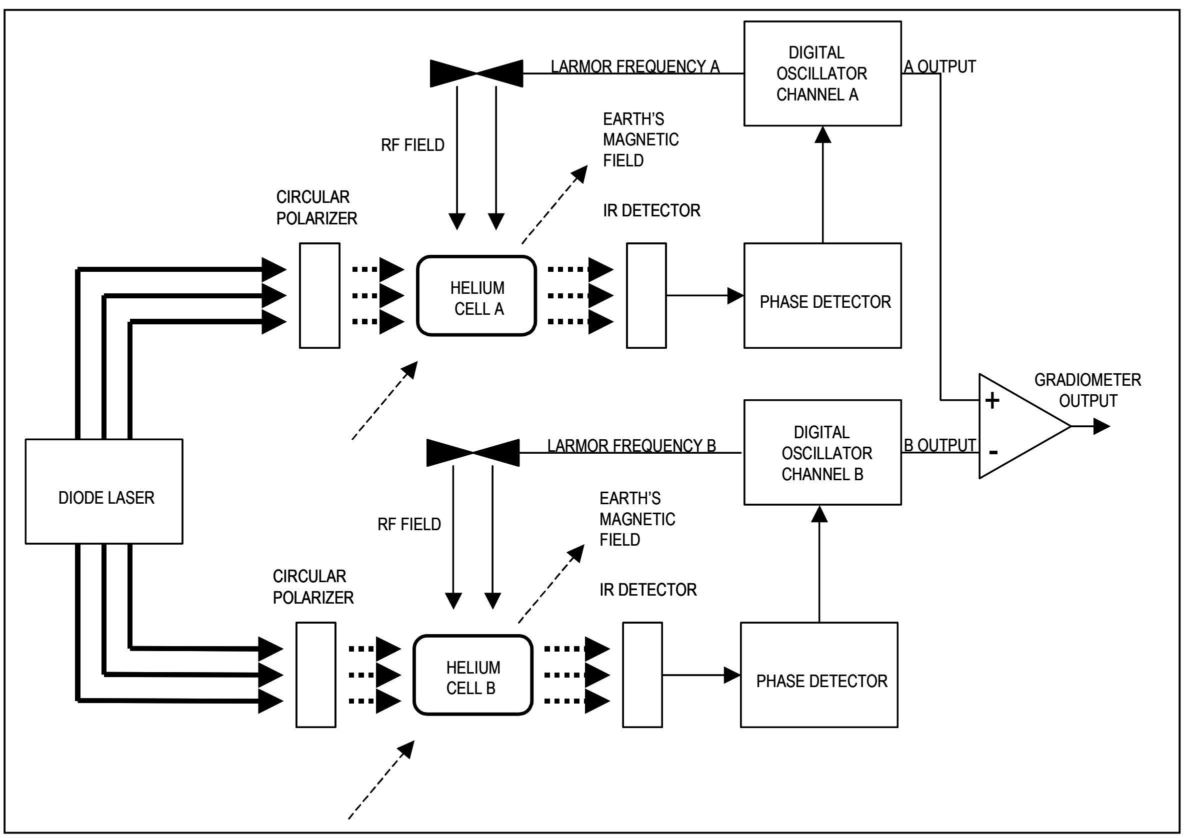

Figure 3. Simplified diagram of the P-2000 Gradiometer operating mode.

3. MAGNETIC SIGNAL SOURCE DETECTION MEASUREMENTS

A series of magnetic signal source measurements using the P-2000 in the Gradiometer mode have been completed at the UTD Magnetic Test facility in Dallas. The magnetic source selected for test was a cylindrically shaped magnet. The dipole strength of the test magnet is 62.3 A-m^2. The magnet has a length of 19 cm and a diameter of 2.5 cm. The magnet was fixed to a disk driven by a small battery powered motor. A gear reduction box mounted between the motor shaft and the disk enabled the magnet to rotate slowly with a period of 8 seconds or 0.125 Hz. This assembly was mounted with the dipole axis of the magnet vertical with respect to the ground. A small cart was used to keep the magnetic source assembly stable and allow towing the source to selected heading and offset distances with respect to the P-2000 sensor head. The signal source is show in Figure 4. The white building in the background contained the P-2000 sensor and is located 100 meters North of the source magnet. The control electronics were located in the dark building to the left.

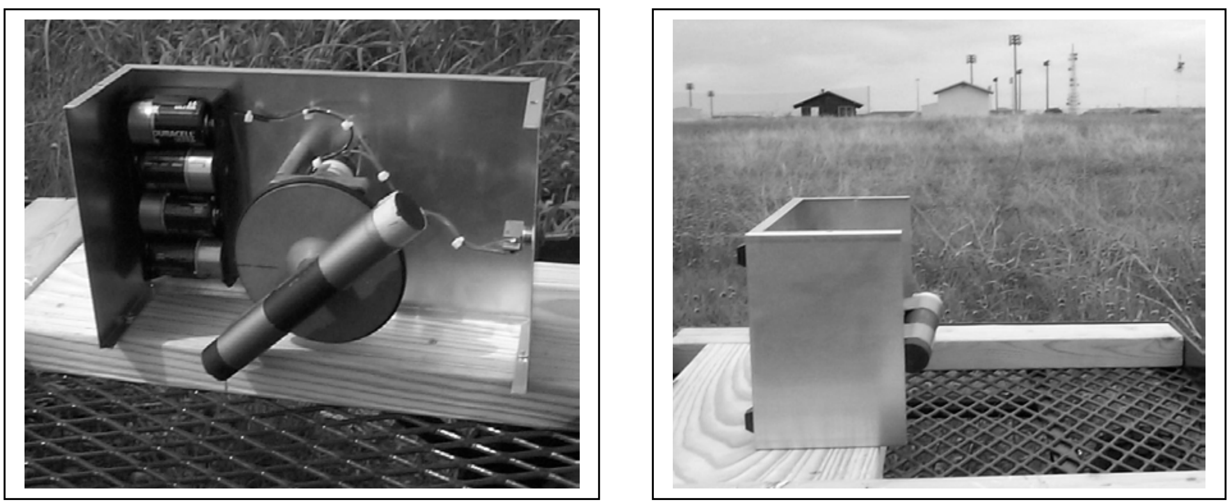

Figure 4. Magnetic signal source at UTD range Dallas with dipole strength 62.3 A-m^2, length 19 cm, and diameter 2.5 cm. Non-magnetic test building 100 meters to the North in the background contained the P-2000 sensor with the cell A to cell B gradiometer alignment North to South. Cell B is North of Cell A.

Figure 5 shows an overview of the test locations and tracks. Point 1 is 100 meters South of the sensor and was the location of static motion tests with magnet rotation. Point 2 to 3 to 2 is the track for a North-South-North run at a 10-meter East CPA offset. Point 4 to 5 is the track for an East to West run at 10 meter South CPA offset. Six minutes of background environmental noise data were collected before the start of the detection testing. The first five minutes of the each data file were analyzed using spectral analysis tools. A total of 131,072 magnet field samples were obtained in this period due to the 432 Hz sample rate of the P-2000 system. A series of four plots are shown in Figure 6. All the plots have three traces with the A and B channels in the upper trace and the Gradiometer output in the lower trace. The A and B traces are overlapping and appear as one trace. The gradiometer subtraction identifies any area of non-coherence between channels A and B. The baseline noise floor is 0.3 pT/√Hz on all four plots. The upper

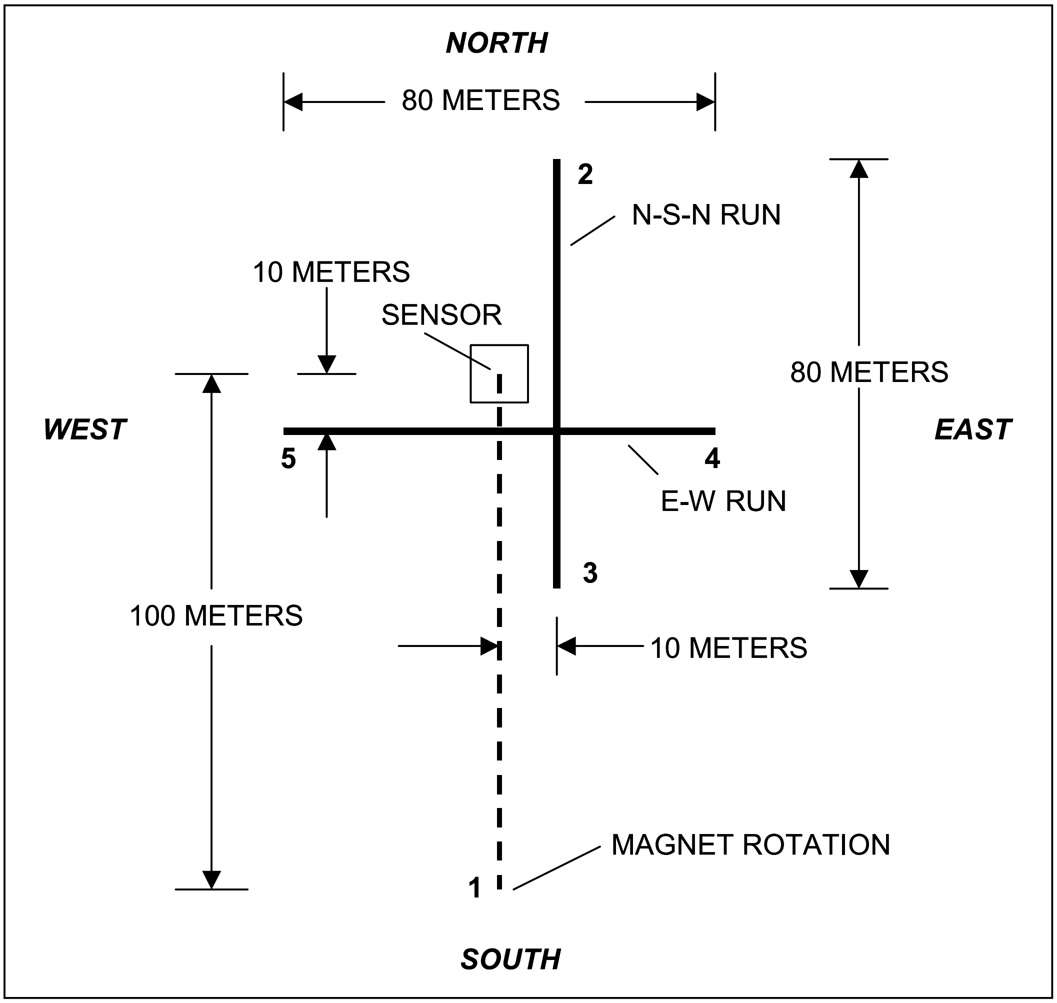

Figure 5. Diagram shows test locations and magnet movement track lines. Static tests with magnet rotation (Figure 6 plots) were at point 1. Magnet movement from point 2 to 3 to 2 (Figure 7 plots) were followed by magnet movement from point 4 to 5 (Figure 8 plots).

left background noise plot shows the characteristic 60 Hz power line signals and also has lines at 39.9Hz and 20.1Hz. The line at 39.9Hz is the Larmor resonance difference between the two channels. Using the gyromagnetic ratio constant for the helium atom of 28.0235 Hz/nT this equates to a 1.424nT magnetic field intensity difference between channels. The 20.1Hz line is the beat frequency difference between the 60Hz and 39.9Hz lines. With the background noise identified, additional data were obtained at distances of 30, 70, and 100 meters South of the P-2000 gradiometer as the North-South aligned magnet was slowly rotated. The new line appears at 0.125Hz. The rotating magnet signal is well above the background noise out to 100 meters. The 70-meter gradiometer trace is shown in the lower left plot. The difference signal is still above the background noise and is detected 70 meters from the source. This is a good example of the sub pT signal measurement capabilities of the P-2000 sensor. Line broadening at 39.9Hz and 20.1Hz due to the magnet rotation is observed as shown in the upper right of the 30-meter plot.

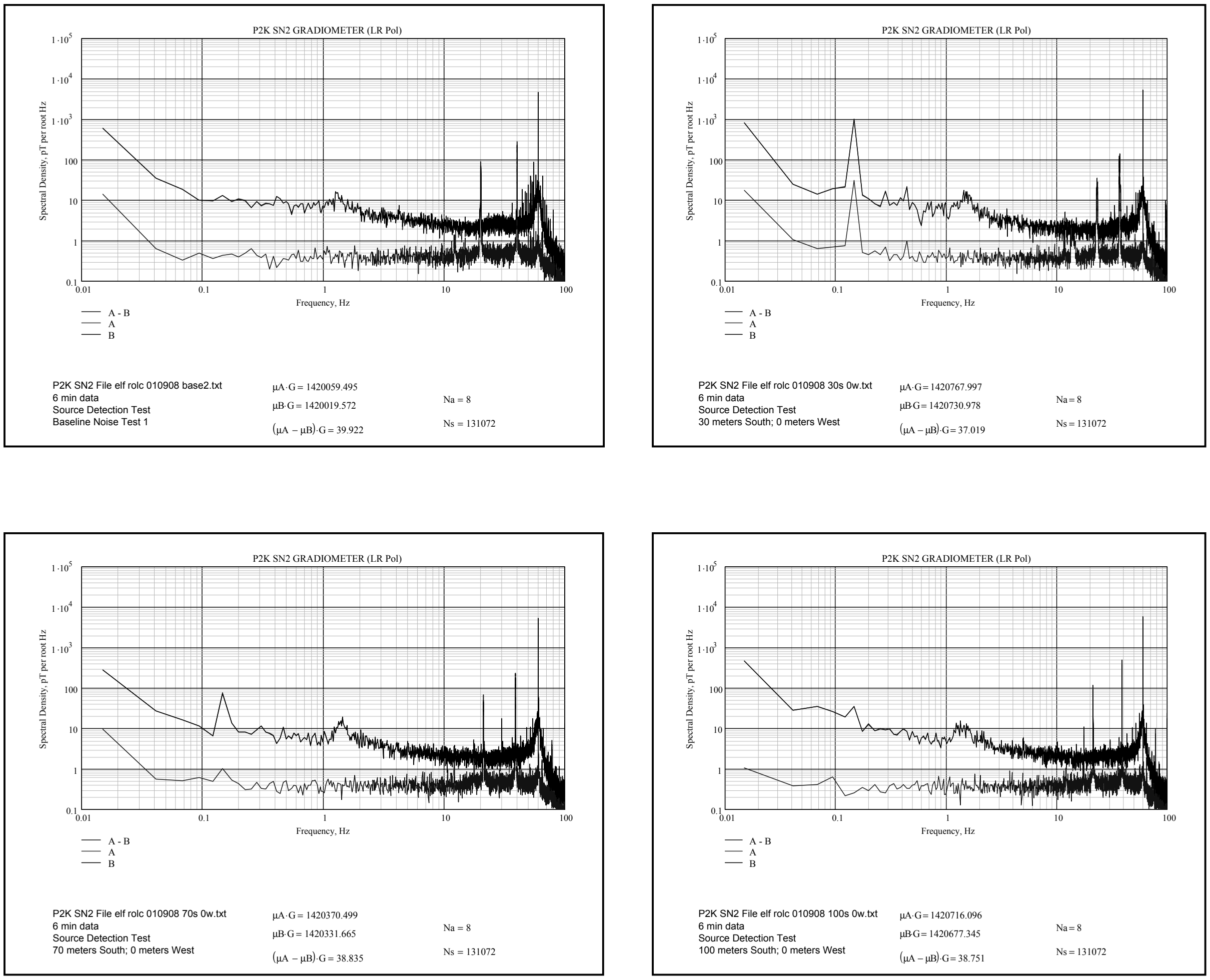

Figure 6. Upper left plot is background environmental noise. Upper right plot is magnet rotation measurement 30 meters to South of sensor. Lower left is 70 meters and lower right plot is 100 meters South of P-2000 gradiometer.

Data were also collected at 10 meter CPA offset distances with the magnet aligned with the 62-degree local magnetic dip angle. Data shown in Figure 7 were collected starting 40 meters North and ending 40 meters South of the P-2000 gradiometer. The cart was then turned 180 degrees and data were collected during a South to North pass at 10 meter CPA offset distance. Direction of motion information can be seen in the gradiometer signal. This is indicated by the negative excursion followed by the positive excursion indicating South as Channel A was positioned South of channel B. This is also verified in the North run data as the positive excursion occurs before the negative excursion. Also note that the cart speed has decreased during the second pass as the time from the gradiometer peak to zero crossing has increased. The reduced amplitude is due to the off dip angle magnet alignment during the North run. Data shown in Figure 8 were collected starting 40 meters East and ending 40 meters West of the P-2000 gradiometer. The positive gradiometer excursion indicates the magnet is South of the sensor. Traces in Figures 7 and 8 demonstrate the value a gradiometer signal can add even though, in this case, most of the signal is common mode to both channels. Using multiple P-2000 sensors with gradiometer spacing great enough to remove environmental noise without canceling signal will yield tracking information in the gradiometer mode while enabling long-

range noise sources such as geomagnetic field disturbances to be removed. In a battlefield environment tank and truck detection and tracking is therefore possible in all weather or day/night conditions as long as motion occurs. Nonmoving targets such as tanks under trees may be detected by moving the sensor as opposed to the tank. Low altitude unmanned aerial vehicle applications are now possible due to the sensitivity improvement realized in the P-2000.

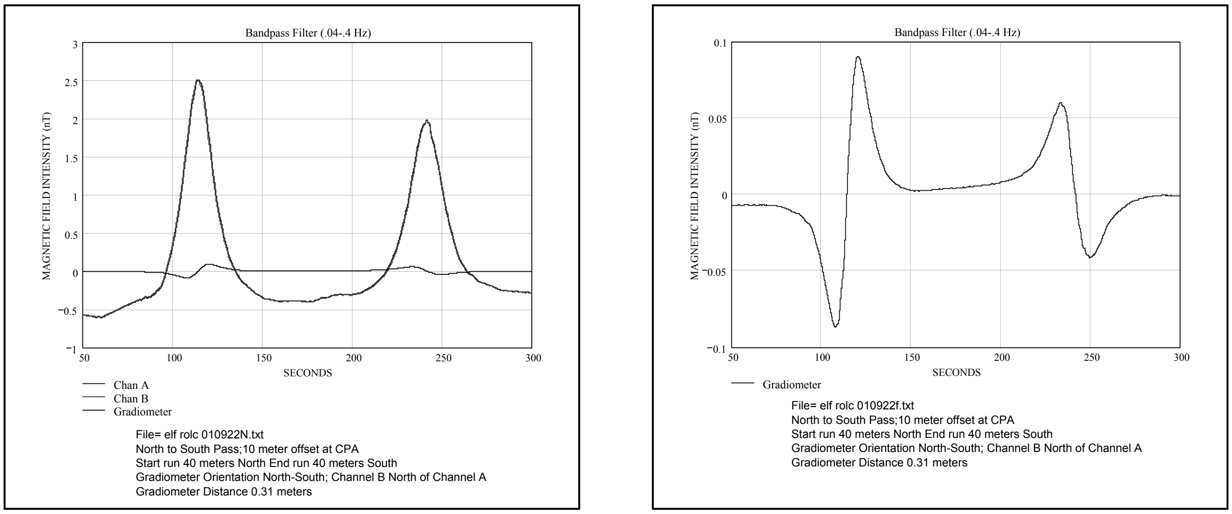

Figure 7. P-2000 gradiometer time series data at 10 meter CPA East offset. Two overlapping traces (Channels A & B) and gradiometer show on left plot. Detail of the gradiometer signal is shown in the right plot. Each plot bandpass filtered (0.04Hz - 0.4Hz). North to South run followed by South to North run.

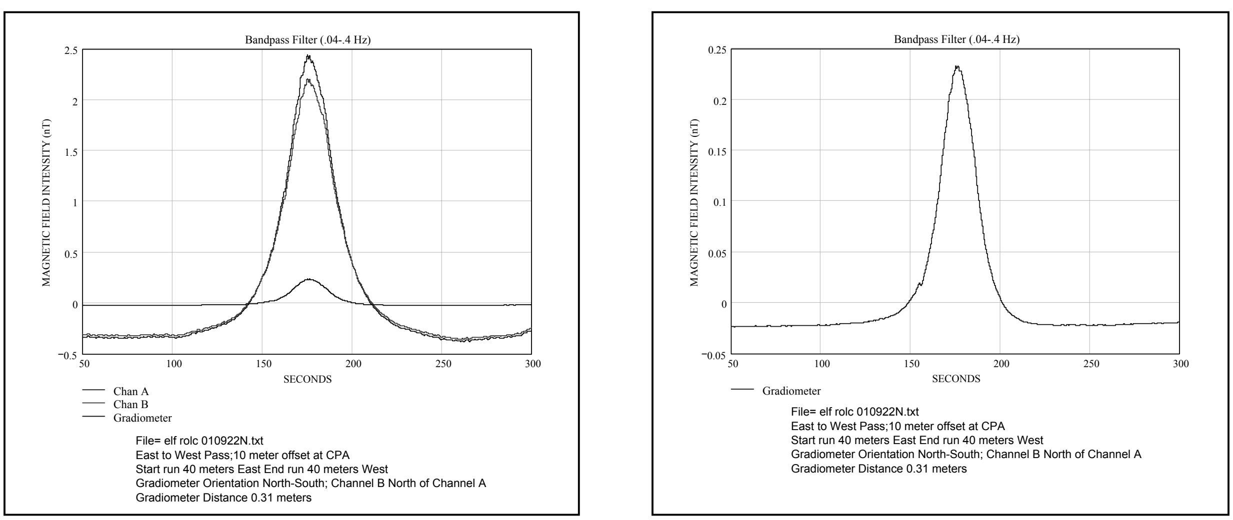

Figure 8. P-2000 gradiometer time series data at 10 meter CPA South offset. Two overlapping traces (Channels A trace upper & B trace lower and gradiometer trace are shown on the left plot. Detail of the gradiometer signal shown in the right plot. Each plot bandpass filtered (0.04Hz – 0.4Hz). East to West run.

4. FLIGHT TESTS

The POLATOMIC 2000 magnetometer system, the ancillary sensors and the data collection system were installed onto a P-3 at Patuxent River, MD. Preliminary ground tests verified the operation of all of the equipment. The first flight test of the P-2000 system was conducted on March 20, 2001. This flight consisted of dedicated maneuvers on cardinal headings, long straight flight legs on cardinal headings, standard rate turns, and both magnetometer and gradiometer data collections. All of the equipment operated at the design performance levels, and data were collected for the entire flight. However, there are several noise sources on this platform that raise the noise floor in different bands above those observed on other P-3 platforms. The current platform noise floor, which is not correlated with maneuvers and buffeting, prohibits effective noise reduction. The focus of future flight efforts will be on a different platform having a normal noise floor. Additional information on aircraft noise sources may be found in reference 1.

5. CONCLUSIONS

Significant sensitivity and signal to noise improvements in scalar magnetometers have been demonstrated. A gradiometer array would enable environmental noise reduction to exploit the sensitivity gain at frequencies below 0.1Hz. Gradiometer arrays enable tracking and classification of magnetic targets in all weather conditions. Magnetic flux lines penetrate through the ground, man made structures, trees, water and clear or smoke filled air. As demonstrated, targets that distort the earth's inherent magnetic flux lines can be detected at significant distances. These detection characteristics make battlefield application of this low noise scalar magnetometer technology important on the ground, from manned airborne platforms and from low-flying UAVs. A program has been initiated under ONR sponsorship to miniaturize the P-2000 for helicopter and UAV installations.

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7. REFERENCES

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